NLO+NLL limits on $W'$, $Z'$ gauge bosons masses in general extensions of the SM

JHEP 1412 (2014) 092

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April 29, 2015
Introduction

- New heavy resonances, $W'$, $Z'$ predicted in a variety of models
  - GUT
  - Extra dimensions

Collider Limits

- SSM, String inspired $Z'$, LR
- Most stringent limits obtained in leptonic final states:
  - $\sim 25$ searches (both ATLAS and CMS)
    $\Rightarrow$ in SSM $M_{Z'} > 2.9$, $M_{W'} > 3.3$ TeV
- Most of them obtained using PYTHIA LO+PS rescaled to NNLO with FEWZ or ZWPROD
  - No interferences with SM $W$ and $Z$ bosons
Introduction

- New heavy resonances, $W'$, $Z'$ predicted in a variety of models
  - GUT
  - Extra dimensions

Our approach:

- Public code RESUMMINO already implements soft-gluon resummation for:
  - $Z'$, gaugino and slepton pair production
  - Added the $W' \rightarrow \ell \nu$ process
- Present QCD resummation predictions for $pp \rightarrow W/W' \rightarrow \ell \nu$
  and $pp \rightarrow Z/Z' \rightarrow \ell \ell$
  - Include the interferences
  - Allow general couplings
- Compare our results with our version of PYTHIA which includes interferences and FEWZ.
I) Introduction

II) Theoretical setup

III) Numerical Results

IV) Gauge boson mass limits in general SM extension

V) Conclusion
**PYTHIA (6.4.27) LO+PS:**

- Implemented the full $qq^{(i)} \rightarrow Z'/W' \rightarrow \ell\ell, (\ell\nu)$
- Includes interferences with $W, Z$ bosons
- Automatic calculation of the total width
- SM like couplings:
  - $\bar{\nu}_\ell \ell W'^+, \bar{\ell}\nu_\ell W'^- \sim \frac{g}{2\sqrt{2}} \gamma^\mu (V_\ell - A_\ell \gamma_5)$,
  - $\bar{q}q' W'^\pm \sim \frac{g}{2\sqrt{2}} U_{CKM} \gamma^\mu (V_q - A_q \gamma_5)$.

**FEWZ LO, NLO, NNLO:**

- Fixed-order, fully exclusive $\rightarrow$ arbitrary cuts
- Extrapolate SM predictions:
  - Fed with the $W', Z'$ bosons properties from PYTHIA
  - Observables need to be rescaled by the proper combination of couplings (not always possible)
- No interferences
**RESUMMINO NLO+NLL:**

- Our implementation of the $W/W'$ and $Z/Z'$ into leptons process
- Resummation of the small $p_T$ and production threshold regions
- Resums the large logarithms in these regions
  - $p_T \to 0$, $z \equiv Q^2/s \to 1$
- Matched to fixed-order NLO calculation
  - $\sigma_{ab} = \sigma_{ab}^{\text{(res.)}} + \sigma_{ab}^{\text{(f.o.)}} - \sigma_{ab}^{\text{(exp.)}}$.
- The code also allows for fixed-order LO, NLO
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Comparison

- Comparison of **RESUMMINO**, **PYTHIA** and **FEWZ** for various models @ **LHC14**

- Sequential Standard Model (SSM), and different realizations of \( G_{221} \) models:
  - \( G_{221} \equiv SU(2)_1 \times SU(2)_2 \times U(1)_X \)
  - Un-unified (UU), Non-Universal (NU)

- In total 5 benchmark points with \( M_{W'} = 4 \) TeV:
  - B1 (SSM), \( \Gamma_{W'} = 143 \) GeV
  - B2 (UU), \( \Gamma_{W'} = 237 \) GeV
  - B3 (UU), \( \Gamma_{W'} = 125 \) GeV
  - B4 (NU), \( \Gamma_{W'} = 217 \) GeV
  - B5 (NU), \( \Gamma_{W'} = 141 \) GeV

- MSTW 2008 global fit at LO, NLO, NNLO and corresponding error sets at 68% C.L.
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$p_T$ spectrum

- SSM, $W^{'+}$ of 4 TeV with $Q_{e+\nu} > 3/4M_{W'}$ to limit interferences and $W$ contribution
**$p_T$ spectrum**

- SSM, $W'^{\pm}$ of 4 TeV with $Q_{e+\nu} > 3/4M_{W'}$ to limit interferences and $W$ contribution

**Total cross sections for the 5 benchmark points:**
  - at LO PYTHIA, FEWZ, RESUMMINO $\sim 1 - 2\%$
  - at NLO RESUMMINO, FEWZ $\sim 1 - 2\%$
Importance of the interferences

- $\sigma: Q_{e+\nu} > 3/4 M_{W'} \Rightarrow \text{Interferences still important}$
  - $Q_{e+\nu} > \xi M_{W'}$
Importance of the Resummation

As the mass increases we probe more and more the threshold region

- NLO + NLL
- NLO
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ATLAS $W'$- SSM

- Re-analysis of the ATLAS results at $\sqrt{s} = 8$ TeV, 20.3 fb$^{-1}$
  - PYTHIA LO+PS, $W^+ + W^-$ with $Q > 0.4M_{W'}$
  - Rescaled to NNLO with ZWPROD $\Rightarrow$ no interferences
  - $M_{W'}^{SSM} > 3.24$ TeV

- $M_{W'}^{RES.} > 3.5$ TeV
ATLAS $W'$ and $Z'$ - UU

- Re-analysis of the ATLAS results at $\sqrt{s} = 8$ TeV, 20.3 fb$^{-1}$

- Res. NLO + NLL/Res. NLO $\simeq$ 20%
- Large interferences
ATLAS $W'$ and $Z'$ - UU

- Re-analysis of the ATLAS results at $\sqrt{s} = 8$ TeV, $20.3$ fb$^{-1}$

![Graph showing limits on $\sigma \times \text{Br}$ in pb vs $M_{W'}$ [GeV] for different theoretical scenarios.]

**Res. NLO + NLL/Res. NLO $\simeq 20\%$**

**Large interferences**

- $M_{W'/Z'}^{\text{RES.}} > 3.9 - 4$ TeV, improves from previous limits obtained from low-energy and precision observables.
- Holds for $Z'$ in UU: $M_{Z'} \simeq M_{W'} + O(v^2/u^2)$
CMS $Z'$- SSM

- Re-analysis of the CMS results at $\sqrt{s} = 8$ TeV, $20.6$ fb$^{-1}$
- PYTHIA LO+PS rescaled @NNLO with ZWPROD
- $0.6M_{Z'} < Q < 1.4M_{Z'} \Rightarrow M_{Z'} > 2.96$ TeV

![Graph showing $R_{\sigma}$ vs. $M_{Z'}$](image)

- Large interferences
- $M_{Z'}^{\text{RES.}} > 3.2$ TeV.
CMS $Z'$ - UU

- Re-analysis of the CMS results at $\sqrt{s} = 8$ TeV, 20.6 fb$^{-1}$
- $0.6M_{Z'} < Q < 1.4M_{Z'}$

- $M_{Z'}^{\text{RES.}}/W' > 2.75 - 3.2$ TeV, previous limits: 2.5 TeV.
Summary

Limits obtained from the Re-analysis

- **SSM:**
  - From ATLAS $W'$ analysis: $M_{W'} > 3.5$ TeV (3.24)
  - From CMS $Z'$ analysis: $M_{Z'} > 3.2$ TeV (2.96)

- **UU:**
  - From ATLAS $W'$ analysis: $M_{W'/Z'} > 3.9 - 4$ TeV
  - From CMS $Z'$ analysis: $M_{Z'/W'} > 2.75 - 3.2$ TeV

- **also NU:**
  - From ATLAS $W'$ analysis: $M_{W'/Z'} > 3.5$ TeV (3.6)
  - From CMS $Z'$ analysis: $M_{Z'/W'} > 3.25$ TeV (3.6)
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Conclusion

- Comparison of $W'$, $Z'$ production @LO, NLO, NNLO, NLO+NLL
- Our implementation, RESUMMINO NLO+NLL is available
- Recast the latest CMS, ATLAS analysis and extracted new limits in the SSM and $G_{221}$ models
- Interferences can be very large in some models and impact strongly the exclusion limits
- Approaching the threshold region with higher masses $\Rightarrow$ Resummation needed
allowed (95\% CL)
Table: Total cross section predictions for positively charged $W'$ bosons decaying into a positron and a neutrino at LHC14 (in attobarns) for the benchmark points defined. Interference terms between $W$ and $W'$ gauge bosons and the pure SM contribution are neglected. The invariant mass of the lepton pair is restricted to $Q > 3M_{W'}/4$. 

<table>
<thead>
<tr>
<th>Model</th>
<th>RESUMMINO LO</th>
<th>PYTHIA LO</th>
<th>RESUMMINO NLO</th>
<th>FEWZ NLO</th>
<th>RESUMMINO NLO+NLL</th>
<th>FEWZ NNLO</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B_1$</td>
<td>1338.6$^{+155.5}_{-186.7}$</td>
<td>1333.0$^{+188.9}_{-155.4}$</td>
<td>1469.2$^{+119.7}_{-134.7}$</td>
<td>1492.9$^{+127.9}_{-79.4}$</td>
<td>1411.2$^{+88.7}_{-37.2}$</td>
<td>1509.1$^{+25.7}_{-34.5}$</td>
</tr>
<tr>
<td>$B_2$</td>
<td>799.2$^{+92.5}_{-111.4}$</td>
<td>799.6$^{+112.2}_{-91.6}$</td>
<td>874.6$^{+73.8}_{-83.9}$</td>
<td>893.5$^{+74.9}_{-47.3}$</td>
<td>843.3$^{+47.5}_{-26.0}$</td>
<td>902.7$^{+12.7}_{-18.4}$</td>
</tr>
<tr>
<td>$B_3$</td>
<td>1515.4$^{+175.3}_{-213.6}$</td>
<td>1520.0$^{+214.9}_{-176.4}$</td>
<td>1672.7$^{+138.9}_{-156.2}$</td>
<td>1689.2$^{+145.2}_{-101.4}$</td>
<td>1605.7$^{+99.7}_{-44.2}$</td>
<td>1705.1$^{+24.2}_{-35.3}$</td>
</tr>
<tr>
<td>$B_4$</td>
<td>3630.9$^{+420.3}_{-506.5}$</td>
<td>3636.9$^{+504.5}_{-427.1}$</td>
<td>3986.9$^{+339.9}_{-375.4}$</td>
<td>4053.5$^{+341.0}_{-236.9}$</td>
<td>3841.5$^{+214.4}_{-112.1}$</td>
<td>4094.5$^{+394.3}_{-247.6}$</td>
</tr>
<tr>
<td>$B_5$</td>
<td>351.2$^{+41.1}_{-49.0}$</td>
<td>349.6$^{+48.9}_{-40.6}$</td>
<td>385.2$^{+31.3}_{-35.7}$</td>
<td>388.9$^{+47.8}_{-20.8}$</td>
<td>369.9$^{+23.4}_{-10.2}$</td>
<td>392.6$^{+38.5}_{-8.1}$</td>
</tr>
</tbody>
</table>
### Table: Same as above, but with interference terms now included.

<table>
<thead>
<tr>
<th>Model</th>
<th>PYTHIA w/o int.</th>
<th>PYTHIA w/ int.</th>
<th>RESUMMINO LO</th>
<th>RESUMMINO NLO</th>
<th>RESUMMINO NLO+NLL</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B_1$</td>
<td>$1333.0^{+188.9}_{-155.4}$</td>
<td>$1237.7^{+175.4}_{-145.5}$</td>
<td>$1241.7^{+147.6}_{-176.1}$</td>
<td>$1379.5^{+113.4}_{-121.1}$</td>
<td>$1313.3^{−92.3}_{−27.9}$</td>
</tr>
<tr>
<td>$B_2$</td>
<td>$799.6^{+112.2}_{-91.6}$</td>
<td>$953.2^{+128.1}_{-108.6}$</td>
<td>$949.0^{+107.6}_{-129.5}$</td>
<td>$1013.8^{+90.3}_{-105.7}$</td>
<td>$993.1^{−37.7}_{−40.0}$</td>
</tr>
<tr>
<td>$B_3$</td>
<td>$1520.0^{+214.9}_{-176.4}$</td>
<td>$1684.3^{+234.3}_{-194.4}$</td>
<td>$1676.9^{+193.5}_{-233.0}$</td>
<td>$1831.2^{+158.9}_{-177.3}$</td>
<td>$1775.6^{−86.7}_{−57.2}$</td>
</tr>
<tr>
<td>$B_4$</td>
<td>$3636.9^{+504.5}_{-427.1}$</td>
<td>$3418.0^{+478.2}_{-404.0}$</td>
<td>$3419.4^{+398.8}_{-481.6}$</td>
<td>$3781.1^{+318.5}_{-343.2}$</td>
<td>$3618.7^{−228.5}_{−90.3}$</td>
</tr>
<tr>
<td>$B_5$</td>
<td>$349.6^{+48.9}_{-40.6}$</td>
<td>$317.9^{+45.3}_{-37.8}$</td>
<td>$317.9^{+37.6}_{-45.8}$</td>
<td>$351.9^{+29.5}_{-32.9}$</td>
<td>$332.7^{−25.4}_{−9.0}$</td>
</tr>
</tbody>
</table>
### Gauge boson mass limits in general SM extension

<table>
<thead>
<tr>
<th>Model</th>
<th>New gauge boson</th>
<th>Previous mass limit [TeV]</th>
<th>New mass limit [TeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>SSM</td>
<td>$W'$</td>
<td>3.27–3.28</td>
<td>3.5</td>
</tr>
<tr>
<td>SSM</td>
<td>$Z'$</td>
<td>2.90–2.96</td>
<td>3.2</td>
</tr>
<tr>
<td>UU</td>
<td>$W'$</td>
<td>2.48</td>
<td>3.9–4.0</td>
</tr>
<tr>
<td>UU</td>
<td>$Z'$</td>
<td>2.48</td>
<td>2.8–3.2</td>
</tr>
<tr>
<td>NU</td>
<td>$W'$</td>
<td>3.56</td>
<td>(3.5)</td>
</tr>
<tr>
<td>NU</td>
<td>$Z'$</td>
<td>3.56</td>
<td>(3.3)</td>
</tr>
</tbody>
</table>

**Table:** Previously obtained exclusion limits, using ATLAS and CMS data for the SSM as well as low-energy and precision data for the UU and NU models, and new exclusion limits, including all interference effects and NLO+NLL corrections, for $W'$ and $Z'$ gauge bosons.
SU(2)$_1$ $\times$ SU(2)$_2$ $\times$ U(1)$_X$  

**Identification**

<table>
<thead>
<tr>
<th>Doublet</th>
<th>Triplet</th>
<th>Bi-doublet</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\phi \sim (1, 2, \frac{1}{2})$</td>
<td>$\phi \sim (1, 3, 1)$</td>
<td>$\phi \sim (2, \bar{2}, 0)$</td>
</tr>
</tbody>
</table>

First Stage

$\langle \phi \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ u_D \end{pmatrix}$

$\langle \phi \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ u_T \end{pmatrix}$

$\langle \phi \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} u \\ 0 \\ 0 \end{pmatrix}$

Second Stage

$H \sim (2, \bar{2}, 0)$

$H \sim (1, 2, \frac{1}{2})$

$\langle H \rangle = \frac{v}{\sqrt{2}} \begin{pmatrix} c_\beta & 0 \\ 0 & s_\beta \end{pmatrix}$

$\langle H \rangle = \frac{v}{\sqrt{2}} \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix}$

LR-D, LP-D, FP-D, HP-D  
LR-T, LP-T, FP-T, HP-T  

U(1)$_{\text{e.m.}}$

UU, NU
<table>
<thead>
<tr>
<th>BP</th>
<th>Model</th>
<th>$SU(2)_{1}$</th>
<th>$SU(2)_{2}$</th>
<th>$U(1)_X$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Left-right (LR)</td>
<td>$\begin{pmatrix} u_L \ d_L \end{pmatrix}$, $\begin{pmatrix} \nu_L \ e_L \end{pmatrix}$</td>
<td>$\begin{pmatrix} u_R \ d_R \end{pmatrix}$, $\begin{pmatrix} \nu_R \ e_R \end{pmatrix}$</td>
<td>$\frac{1}{6}$ for quarks, $-\frac{1}{2}$ for leptons.</td>
<td></td>
</tr>
<tr>
<td>Lepto-phobic (LP)</td>
<td>$\begin{pmatrix} u_L \ d_L \end{pmatrix}$, $\begin{pmatrix} \nu_L \ e_L \end{pmatrix}$</td>
<td>$\begin{pmatrix} u_R \ d_R \end{pmatrix}$;</td>
<td>$\frac{1}{6}$ for quarks, $Y_{SM}$ for leptons.</td>
<td></td>
</tr>
<tr>
<td>Hadro-phobic (HP)</td>
<td>$\begin{pmatrix} u_L \ d_L \end{pmatrix}$, $\begin{pmatrix} \nu_L \ e_L \end{pmatrix}$</td>
<td>$\begin{pmatrix} \nu_R \ e_R \end{pmatrix}$;</td>
<td>$Y_{SM}$ for quarks, $-\frac{1}{2}$ for leptons.</td>
<td></td>
</tr>
<tr>
<td>Fermio-phobic (FP)</td>
<td>$\begin{pmatrix} u_L \ d_L \end{pmatrix}$, $\begin{pmatrix} \nu_L \ e_L \end{pmatrix}$</td>
<td></td>
<td>$Y_{SM}$ for quarks, $Y_{SM}$ for leptons.</td>
<td></td>
</tr>
<tr>
<td>Un-unified (UU)</td>
<td>$\begin{pmatrix} u_L \ d_L \end{pmatrix}$</td>
<td>$\begin{pmatrix} \nu_L \ e_L \end{pmatrix}$;</td>
<td>$Y_{SM}$ for quarks. $Y_{SM}$ for leptons.</td>
<td></td>
</tr>
<tr>
<td>Non-universal (NU)</td>
<td>$\begin{pmatrix} u_L \ d_L \end{pmatrix}<em>{1^{st},2^{nd}}$, $\begin{pmatrix} \nu_L \ e_L \end{pmatrix}</em>{1^{st},2^{nd}}$</td>
<td>$\begin{pmatrix} u_L \ d_L \end{pmatrix}<em>{3^{rd}}$, $\begin{pmatrix} \nu_L \ e_L \end{pmatrix}</em>{3^{rd}}$;</td>
<td>$Y_{SM}$ for quarks. $Y_{SM}$ for leptons.</td>
<td></td>
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